

# Extreme Astronomy : Neutrinos from Beyond the Edge

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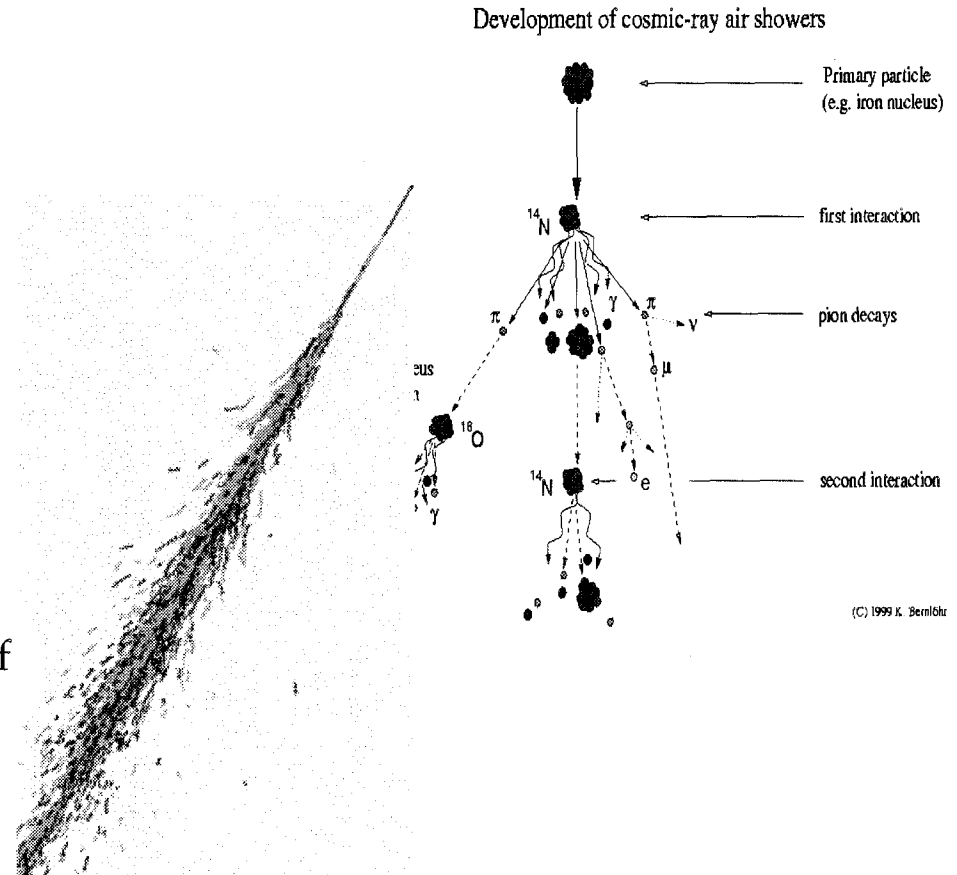
# A (very) Brief History of Cosmic Rays



Victor Hess, 1912:  
- discovered cosmic rays in  
balloon flights, through  
discharge of Leyden jars

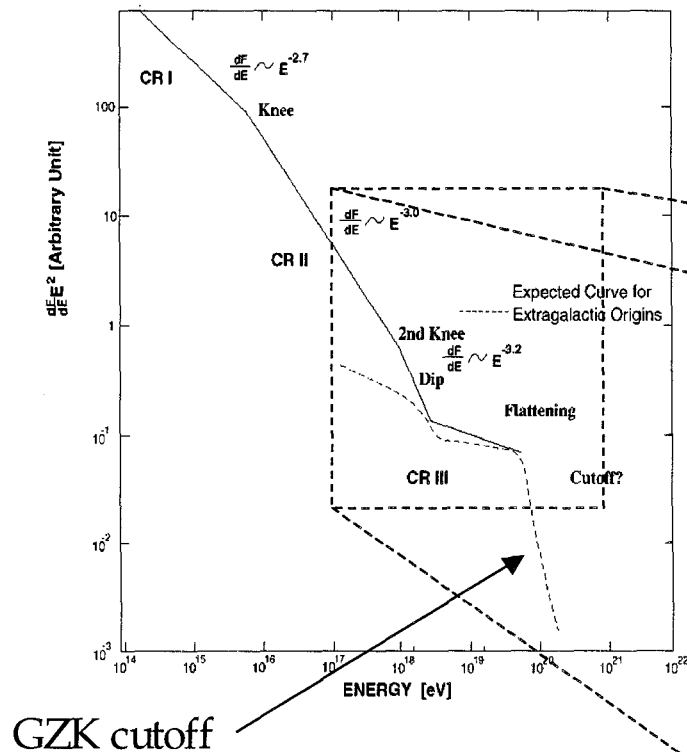


Pierre Auger, 1938:  
- Research in Giant Air  
Showers showed energies of  
primary particles above  
 $10^{16}$  eV-- truly  
unimaginable for the time!

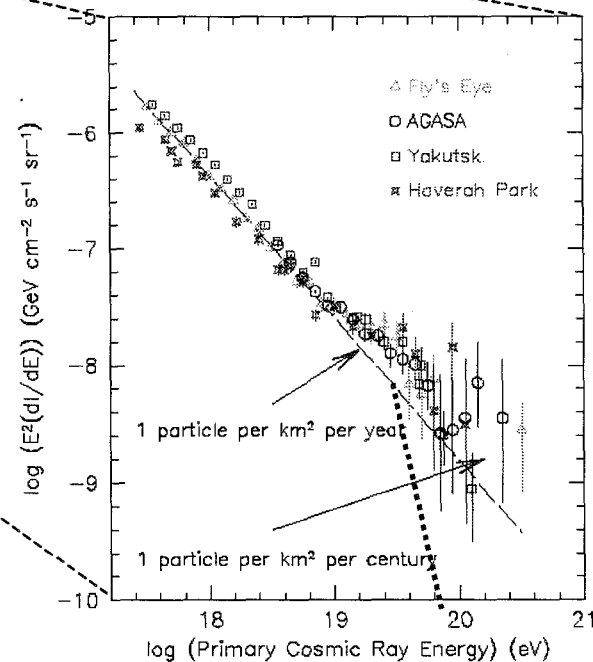


- 1960's: Cosmic rays with energies of  $>10^{19}$  eV detected--how are they made??
- Greisen, Zatsepin, Kuzmin (GZK): there should be a limit at  $\sim 5 \times 10^{19}$  eV
  - *But no such cutoff has yet been seen--energies up to  $3 \times 10^{20}$  eV detected!*

# EHE Cosmic Rays & The GZK edge



EHE cosmic rays--almost certainly extragalactic...if protons or nuclei, MFP in 3K photon background is ~10Mpc--the very local universe!



But no GZK edge is yet seen--if anything there is an enhancement where the cutoff should be....

## EHE cosmic ray demographics

- $3 \times 10^{20}$  eV cosmic ray proton  $\Rightarrow E = 50$  J  
 $\Rightarrow$  similar to a major-league fastball (could kill you!)
- If a 100 microgram meteor (typical of smallest grains) had the same speed:
  - Equivalent energy  $\Rightarrow$  10 million Mton bomb (eg, Mt St. Helens++)
- If a baseball had the same speed:
  - Equivalent to a 200km diameter asteroid hitting the earth  
 $\Rightarrow$  would destroy all life!!

## Above 10 TeV: Neutrino astronomy is the *only* complete astronomy

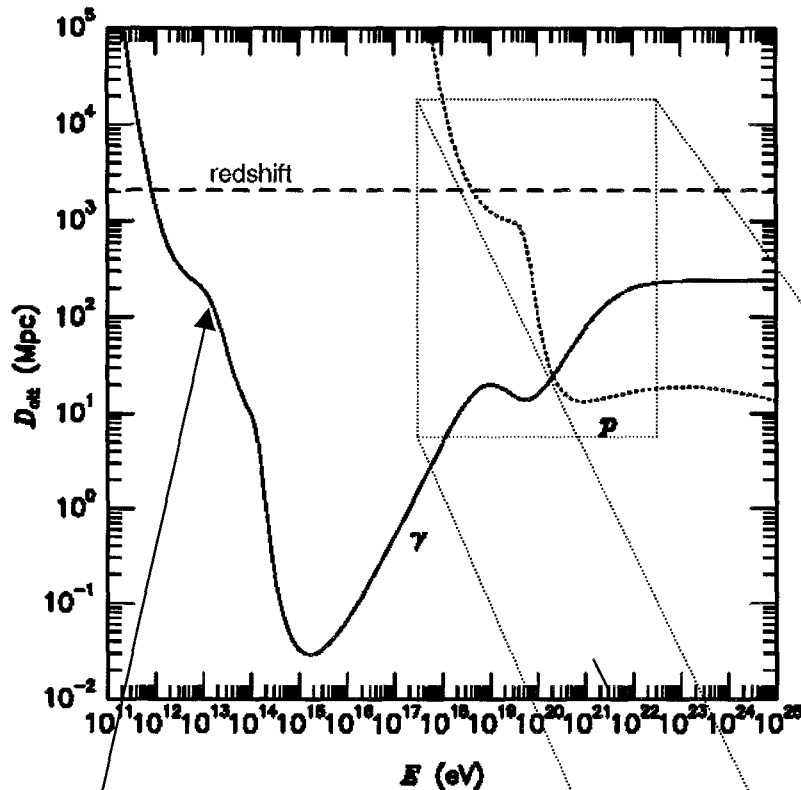
- Gamma-rays interact with IR bkg
- EHE protons & nuclei interact with 3K microwave photons

=> Photon & CR astronomy are limited  
to the local ~100 Mpc volume

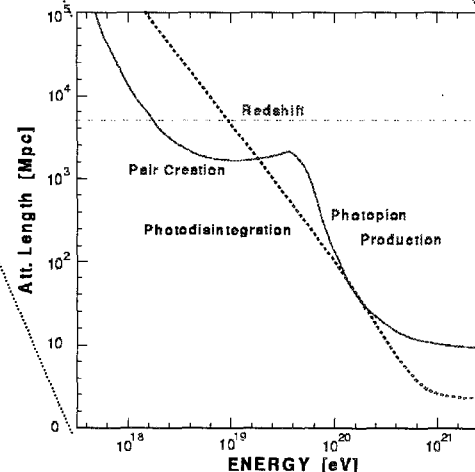
=> *Less than 0.1% of the visible  
universe to  $z \sim 3$*

- The universe is  
transparent to neutrinos at  
all energies

(But not completely...)



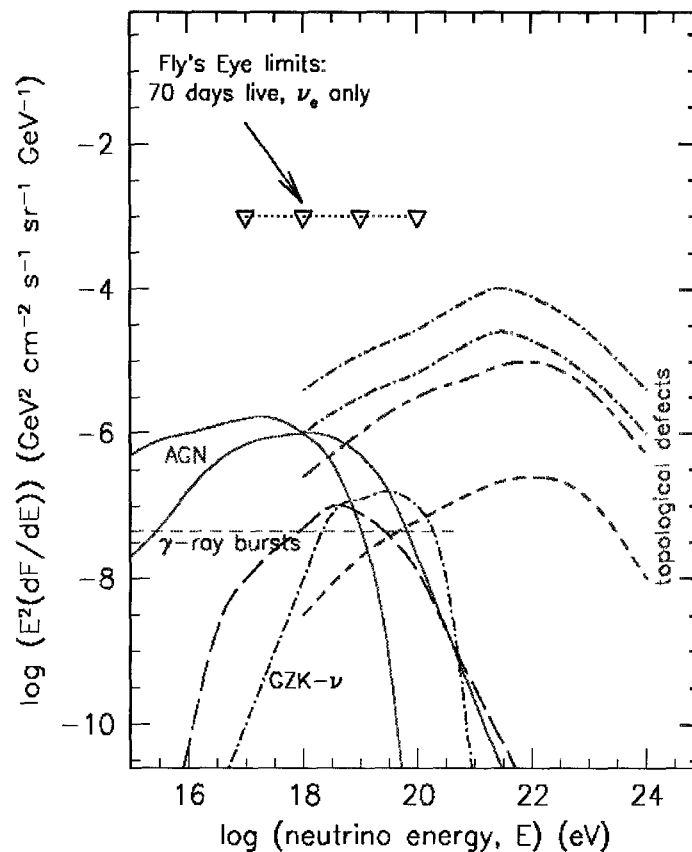
Highest photon  
energies observed:  
TeV blazars  
MRK421 & 501,  
& Crab Nebula



## Neutrinos & EHE Cosmic Rays: What's the connection?

- Neutrinos may provide a solution to bridge the GZK edge
  - ZeV neutrinos can propagate from anywhere in the universe
  - May interact with clustered relics in galactic halo to produce secondary hadrons (Gelmini & Kusenko 1999)
  - Z-burst process: ZeV neutrino pair annihilation with relic neutrinos  
==> Z<sub>0</sub> particles, decays make hadrons (T. Weiler, 1986++)
- EHE neutrinos are secondaries of GZK process
  - if EHE cosmic ray sources are distant, neutrinos are inevitable byproduct of the photopion interaction
- ==> *Constraints on EHE neutrinos are necessary & in some cases sufficient to determine super-GZK physics*

# Sources of PeV to ZeV Neutrinos



## Almost certain sources :

- Extragalactic cosmic rays
  - Produce the so-called GZK neutrinos
  - $10^{20}$  eV cosmic rays from  $z \sim 1-10$  lead to EeV neutrinos through photopion interactions

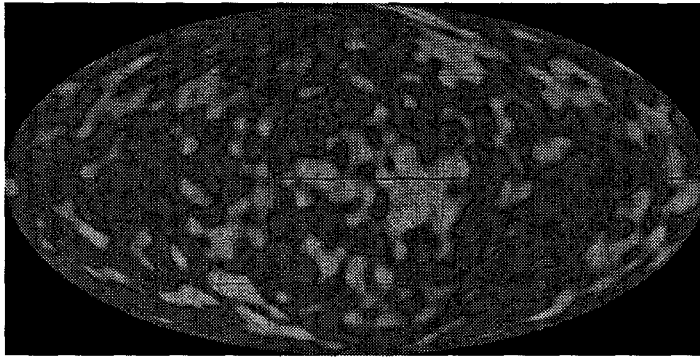
## Probable sources:

- Active galaxies:
  - strong evidence for acceleration of particles, EeV energies probable
- Gamma-ray bursters:
  - PeV to EeV predicted by many models

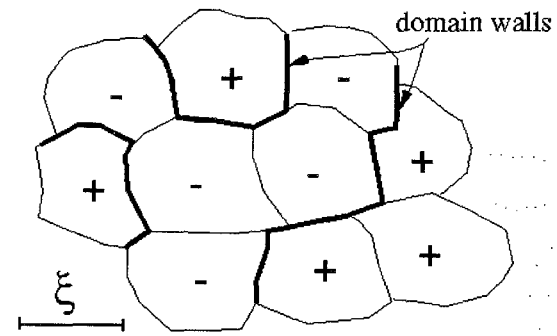
## Exotic (but very interesting) sources:

- Topological defects
  - early universe relics ( of many sorts)

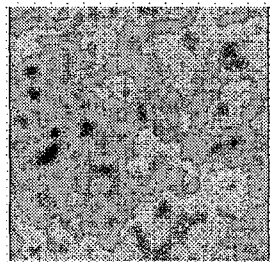
# Topological Defects: Possible EHE neutrino sources



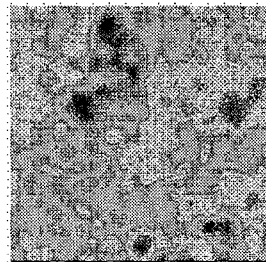
Cosmic microwave background--light echoes from the Big Bang: why the ripples?



Domains are the “causal contact” regions: the domain wall is a 4-dimen horizon over which there is no contact



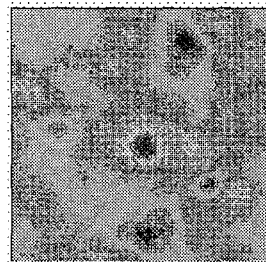
*Inflation*



*Cosmic strings*

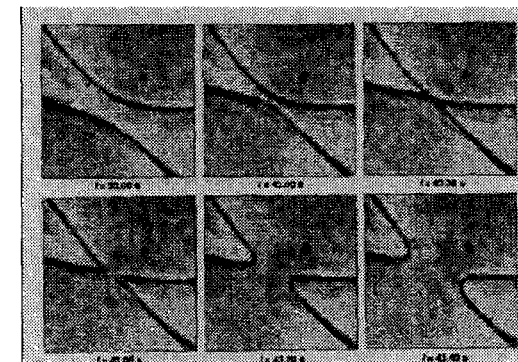


*Global monopoles*



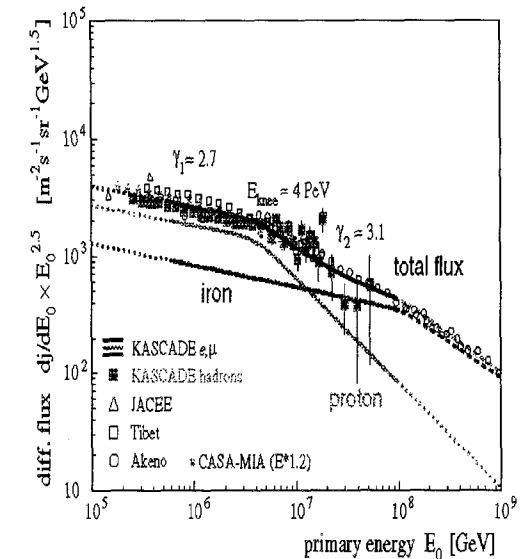
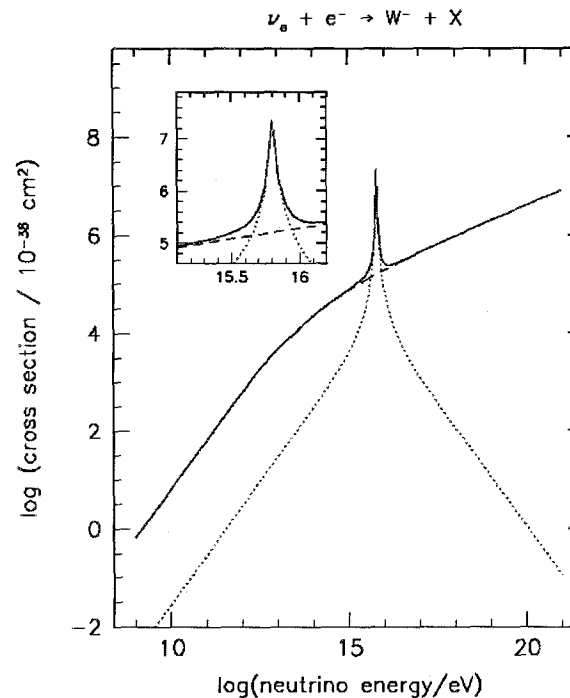
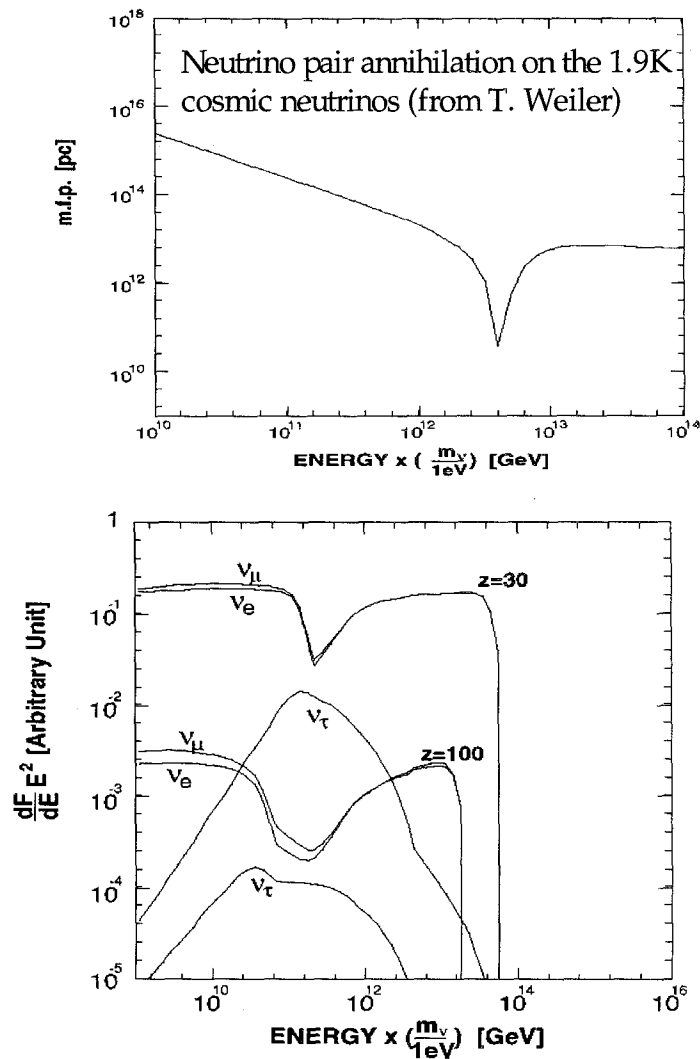
*Texture*

Ripples are caused by the state of the “surface” of our part of the universe when it lost contact with other domains during early universe inflationary epoch



Topological defects are relics of distortions caused by these domains--here a similar effect occurs in a liquid crystal on a micro-scale

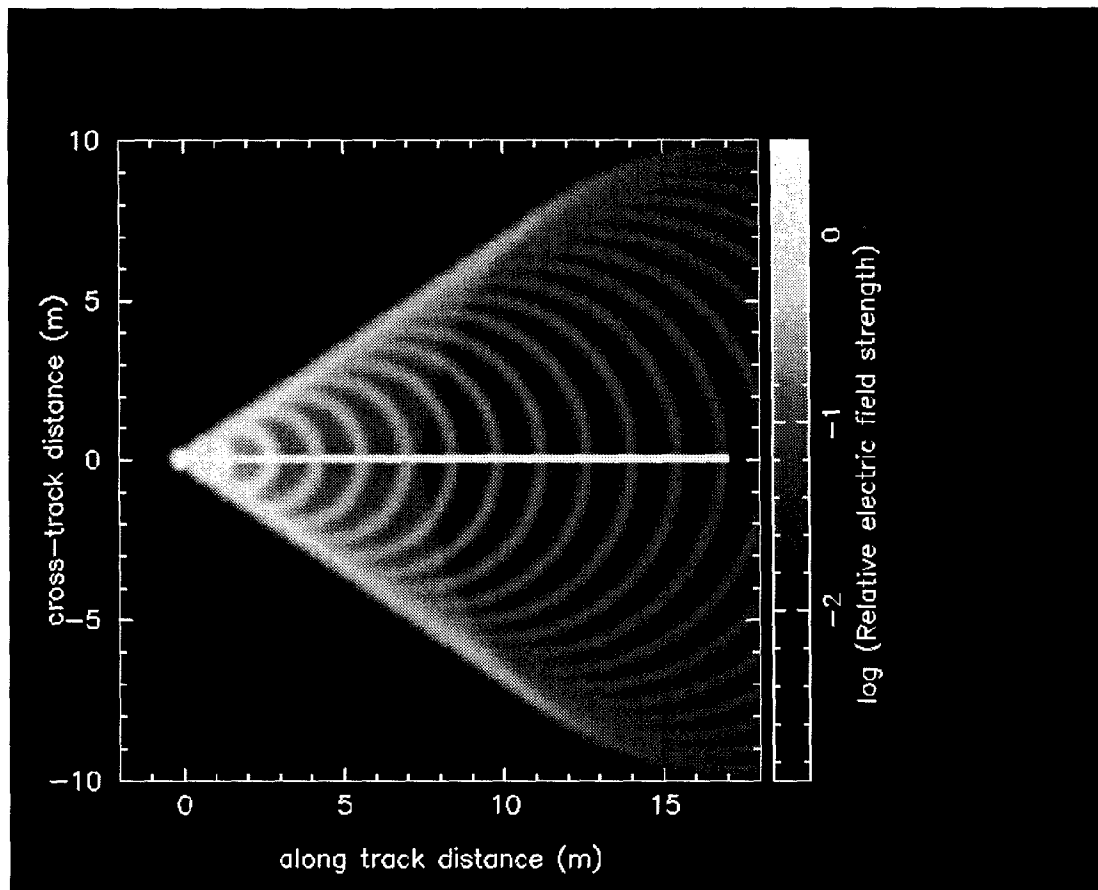
# PeV to ZeV Neutrino spectroscopy



- 6.4 PeV Glashow resonance: electron neutrino cross section greatly enhanced
- Likely to have astrophysical importance
- *Are there other unforeseen features?*

- Requires sources of  $> 10^{22}$  eV neutrinos
- One of few possible ways to verify 1.9K neutrinos

# How to detect neutrinos? Cherenkov Radiation



- “Huygens construction” of Cherenkov radiation
- $n \sim 1.5$ , wavefronts move at  $c/n$ , particles at  $c$
- Fields add up at angle  $= \cos^{-1}(1/n)$

- Neutrinos are the fire:  
=> Cherenkov radiation is the “smoke”

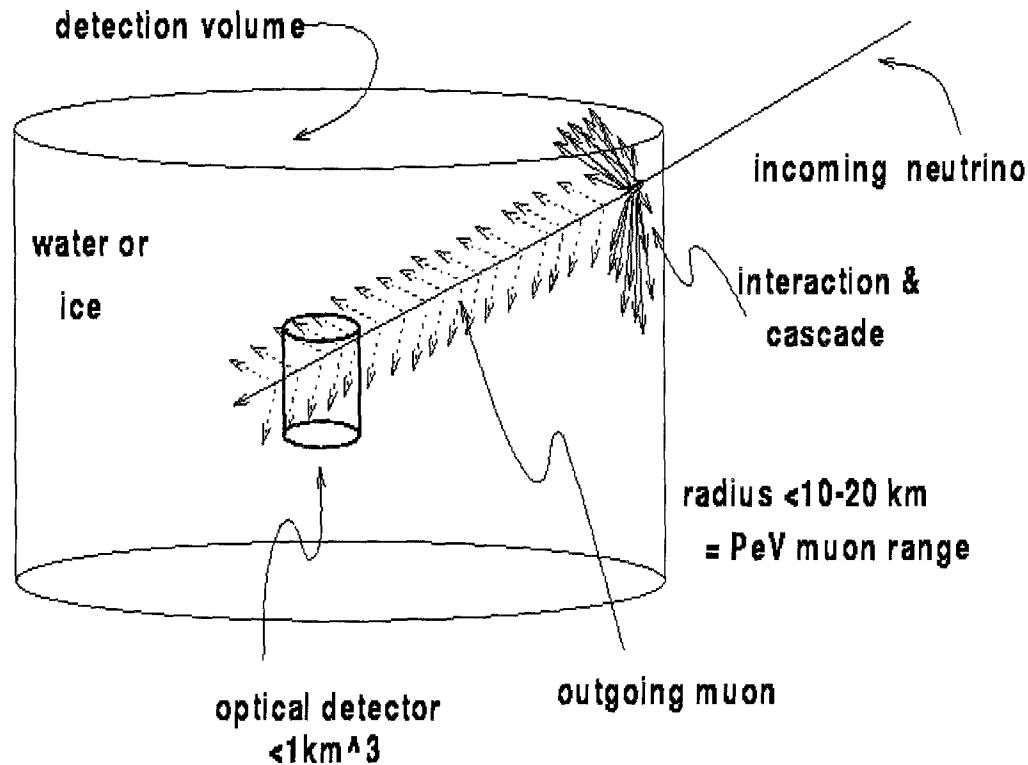
- Neutrino interactions: local, intense cascade + far-ranging muons, all at  $\sim$ vacuum speed of light

- Speed-of-light in matter can be 40-50% slower than in a vacuum

- Electromagnetic wakefields result in a kind of EM shock wave => Cherenkov Radiation

- CR produced from radio through optical and UV

# PeV to ZeV Neutrino Cherenkov Telescopes: Muon rangers vs. cascade detectors

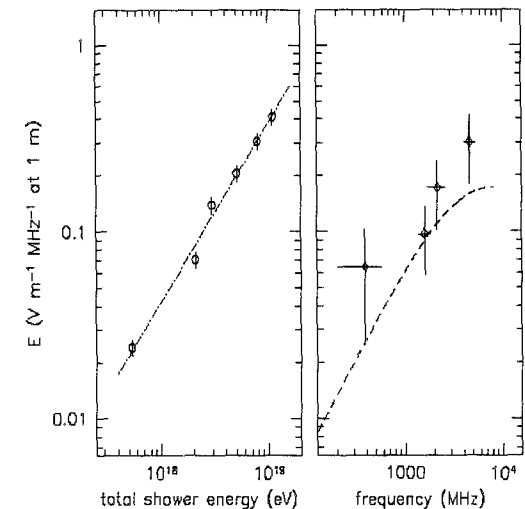
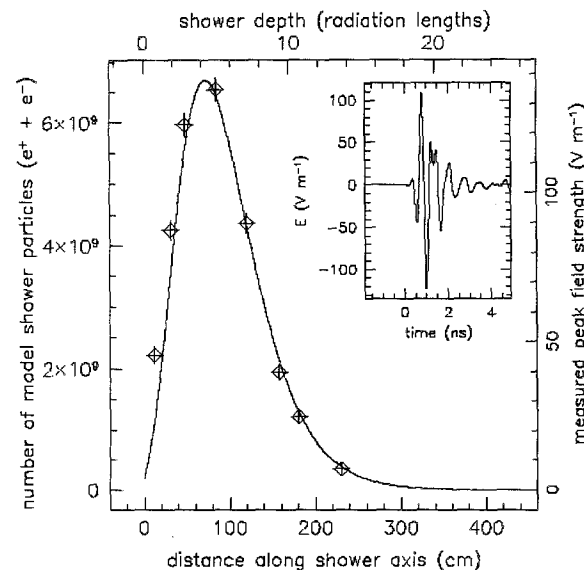
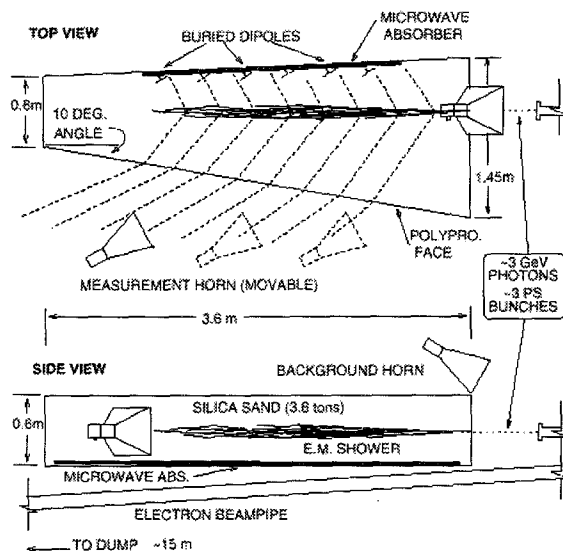


- Muon ranges in water & ice are up to  $\sim 20\text{ km}$  in TeV to PeV  
=> *Relatively small target volume sees a large neutrino volume*
- Examples: AMANDA, ANTARES, NESTOR, Baikal
- **Limitations:**
  - Mu range limits volume for EeV neutrinos
  - Poor energy resolution
- **Cascade Detectors:** Look for large burst of CR from primary cascade
- Requires very clear media to allow for coarse sensor spacing
- “Calorimeter” approach
- Can use external sensors for  $>\text{EeV}$

*Need large volumes of transparent material!*

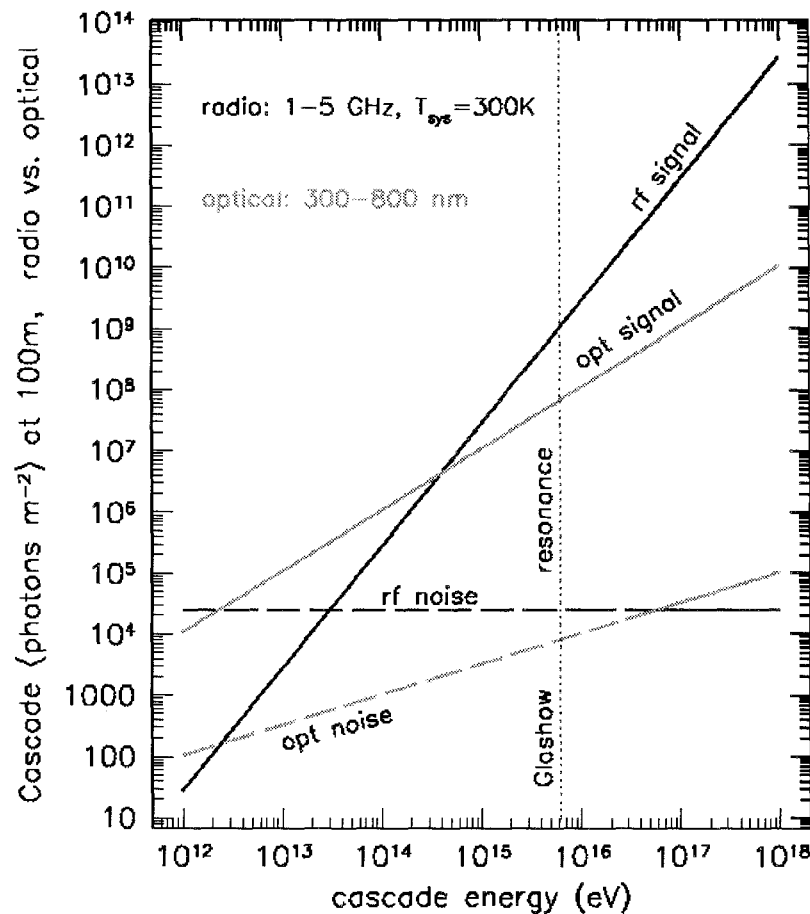
## Cascade Radio emission: The genius of G. Askaryan

- Electromagnetic showers composed of gamma-rays,  $e^+$ ,  $e^-$  primarily  
 $\Rightarrow$  should be electrically neutral overall, thus *no net radio emission*
- G. Askaryan (1962,65) realized that scattering processes & positron annihilation lead to a 15-30%  $e^-$  excess
- This can radiate *coherent Cherenkov* radiation  $\Rightarrow$  Power  $\sim$  energy<sup>2</sup>
- Effect only confirmed within the last year at SLAC--but it is a *strong effect* !



From Saltzberg, Gorham, Walz et al 2001, PRL (in press)

# Detecting the PeV to EeV cascade: Radio vs. optical



- Optical Cherenkov: strong in blue to UV--good match for PMTs
    - Signal is incoherent => intensity grows linearly with cascade energy
    - Noise floor is due to shot noise, grows as  $\sqrt{\text{signal}}$
  - Radio Cherenkov: broad spectrum, few MHz to  $\sim 10$  GHz
    - Intensity (Power) grows quadratic with shower energy, thermal noise constant
    - RF SNR exceeds optical at  $\sim \text{Pev}$  energies for 100 m distance to shower
- ==> For  $>\text{PeV}$  cascade detection, the radio technique appears to dominate over the optical--if radio-clear shower media can be found (but optical techniques are proven)

# Active PeV to ZeV Neutrino Experiments

## Optical

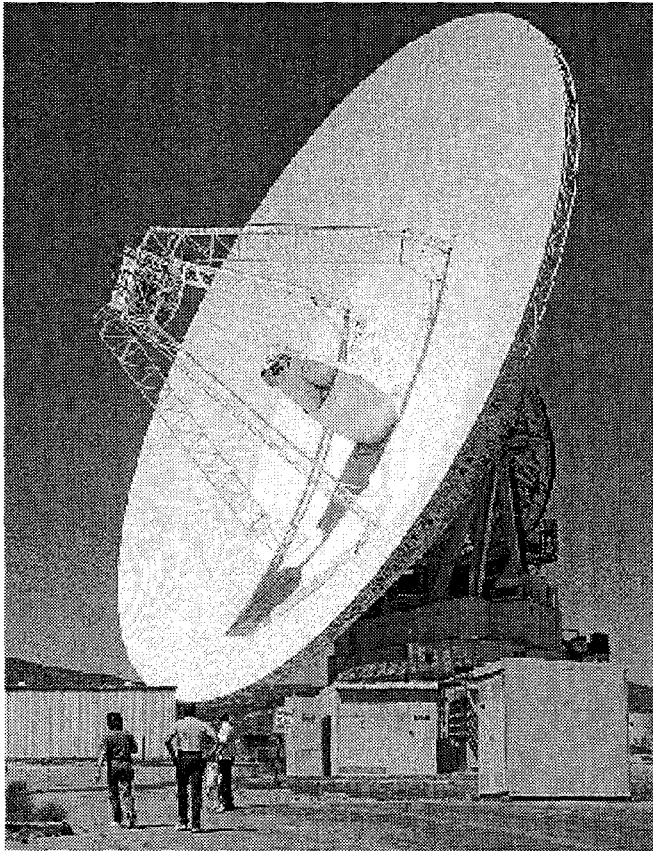
- Antarctic Muon And Neutrino Detector Array (AMANDA)
  - 1-2 km depth in south pole ice
  - Threshold is  $\sim$ TeV  $\Rightarrow$  atmospheric background neutrinos dominate statistics
  - tracking limited by milky ice
- Lake Baikal experiment
  - depth  $\sim$ 1km in fresh water lake
  - limited by water clarity

## Radio

- Radio Ice Cherenkov Experiment (RICE)
  - 200-400 MHz dipole antennas at few hundred m depth above AMANDA (on AMANDA cables)
  - Taking data now since  $\sim$ 97-98
  - limited by RF interference from surface, but not seriously
  - ice is very clear-- attenuation lengths hundreds of m,  $\sim$ 10 PeV threshold
- Goldstone experiment (JPL, UCLA)
- FORTE (serendipity?)

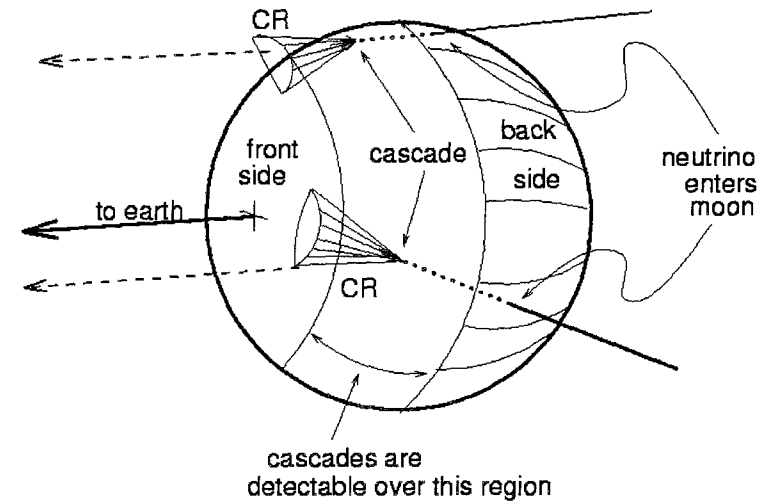
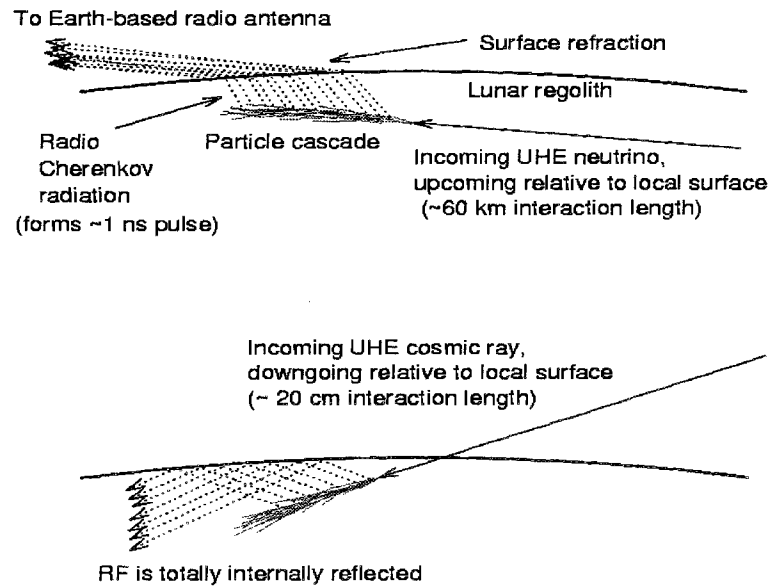
Giant Air shower arrays (AGASA, HiRes) also can detect neutrinos, but limits & sensitivity have been hard to interpret (*or just plain wrong!*)

# Goldstone Lunar Ultra-high energy neutrino Experiment (GLUE)

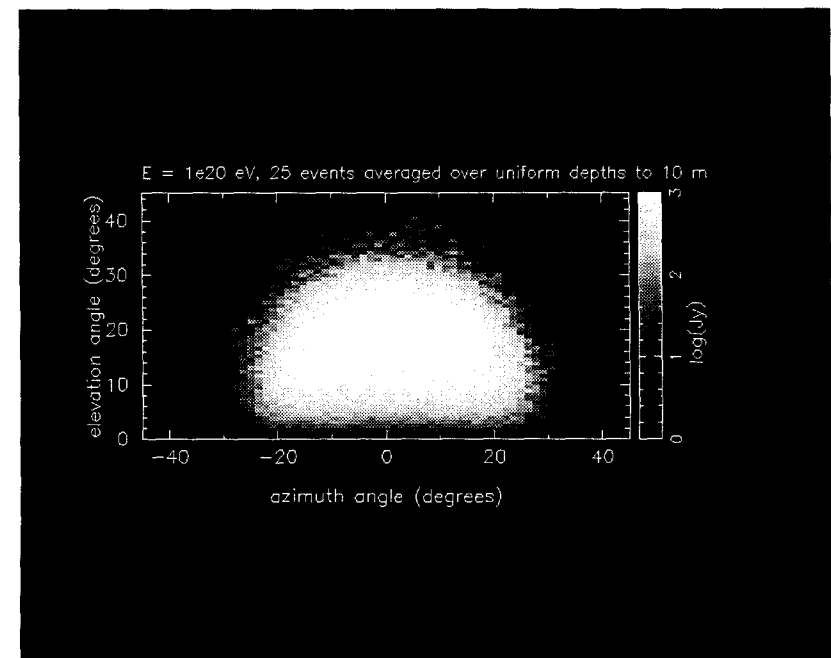


- Utilize Deep Space telecom 70m antenna DSS14 for lunar RF pulse search--fill gaps in SC sched.
- First observations late 1998:
  - approach based on Hankins et al. 1996 results from Parkes 64 m telescope (10hrs live)
  - idea due to I. Zheleznykh, Neutrino '88
  - utilize active RFI veto
- Early 1999: add 2nd 34 m fiber-linked antenna DSS13
  - initially used passive recording with local trigger at DSS14
- 2000: DSS14 down for first half, but ~20 hours livetime acquired since July
  - focussed on limb observations, lower threshold, better trigger system

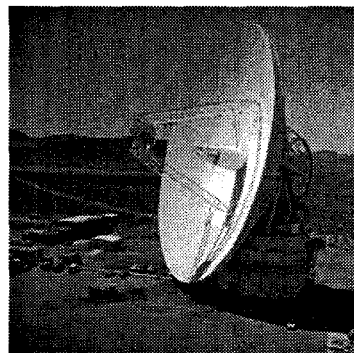
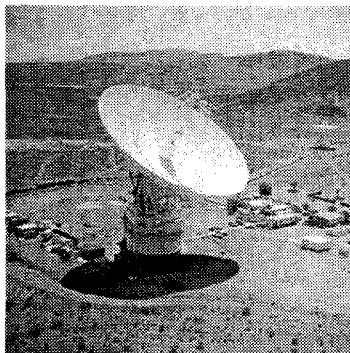
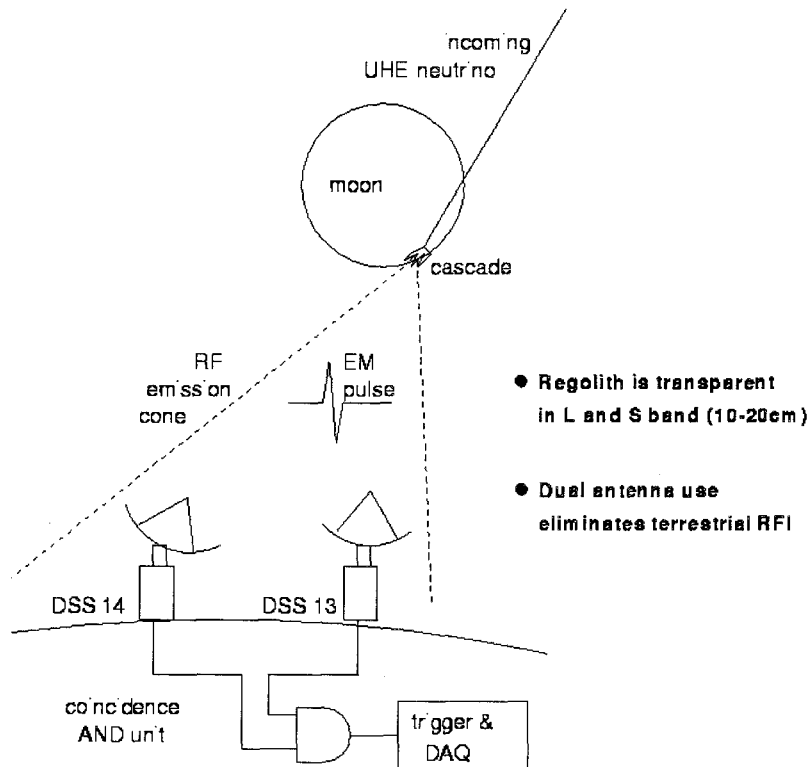
# Lunar Regolith Interactions & RF Cherenkov radiation



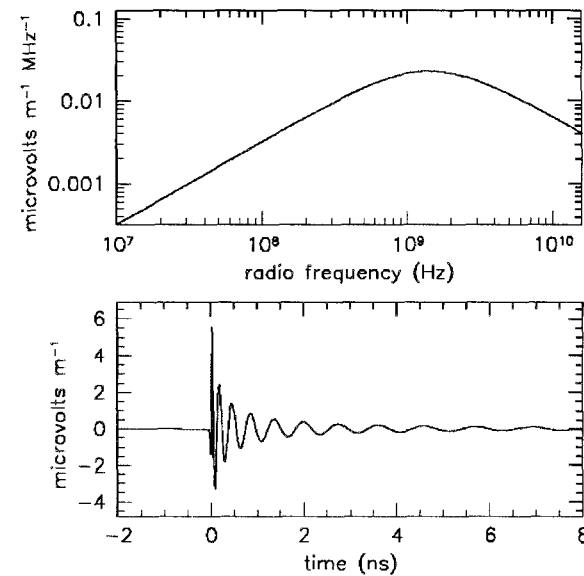
- At ~100 EeV energies, neutrino MFP in lunar material is ~60km
- $R_{\text{moon}} \sim 1760\text{km}$ , so most detectable interactions are grazing rays, but detection not limited to just limb
- Refraction of Cherenkov cone at regolith surface "fills in" the pattern, so acceptance solid angle is ~50 times larger than apparent solid angle of moon



# Goldstone DSN Radio Detection Approach



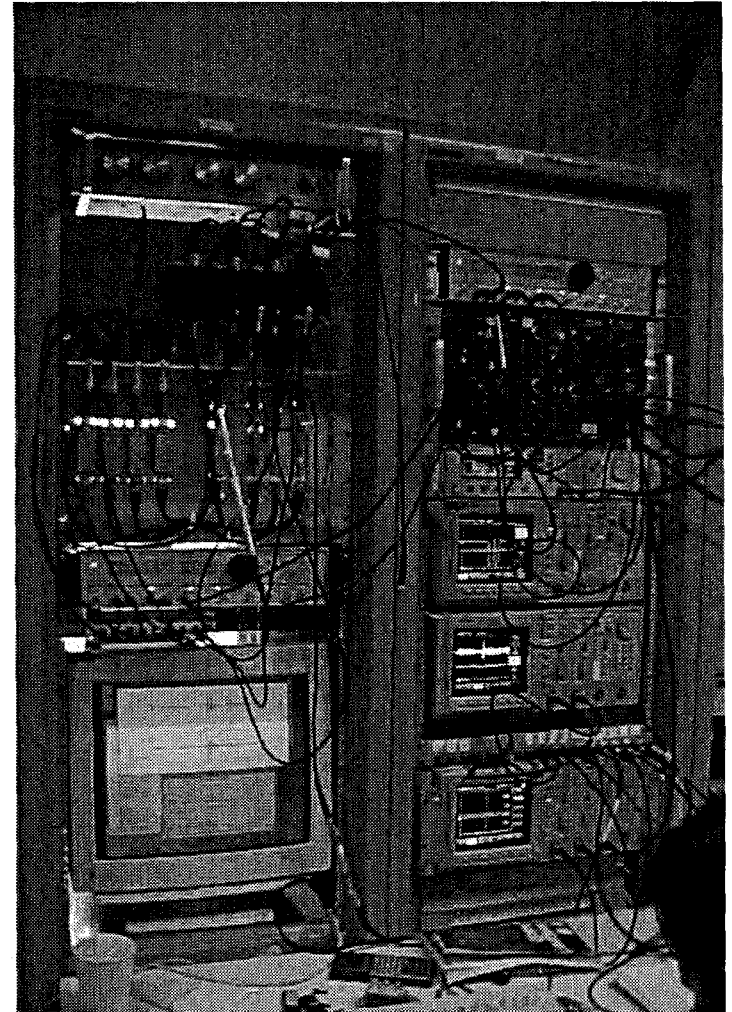
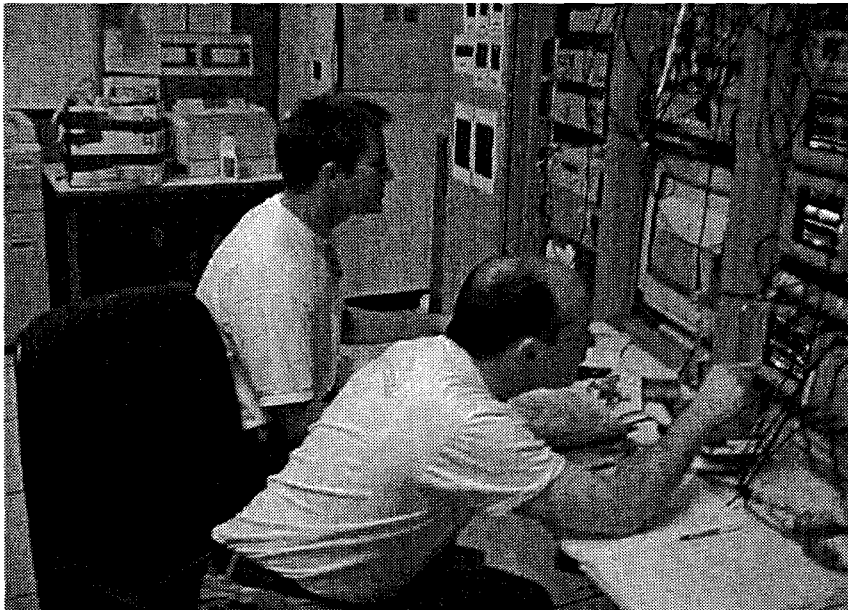
- RF pulse spectrum & shape



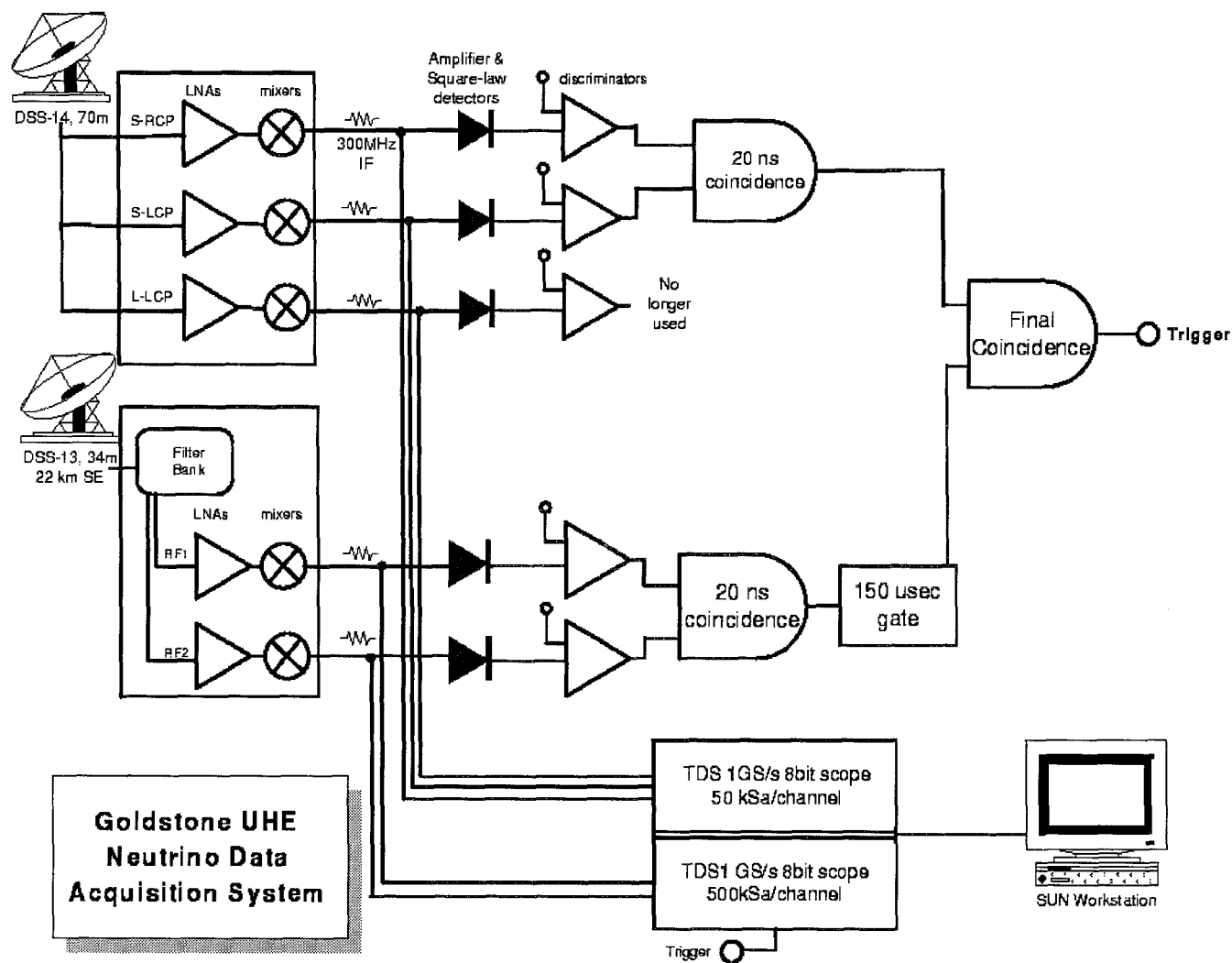
- Effective target volume: Antenna beam ( $\sim 0.3$  deg) times  $\sim 10$  m moon surface layer  
 $\implies \sim 100,000$  cubic km!!
- Limited primarily by livetime--only a small portion of antenna time can typically be devoted to 1 project

# GLUE setup in pedestal at DSS14

- Two relay racks of our own
- JPL tech support
- DSN committed to ~120+ hours of exposure per year for several more years
- New trigger: RF front end, HEP back end

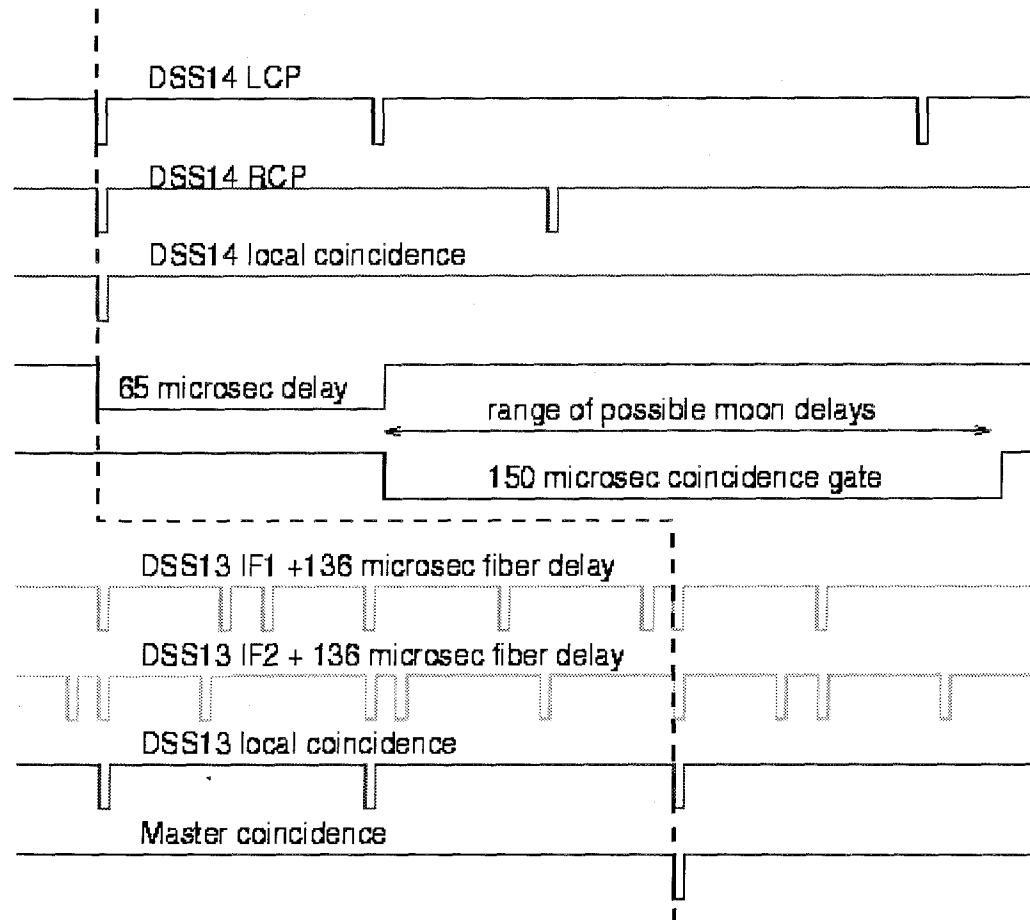


# GLUE Trigger/DAQ



- RFI veto:
  - no longer in trigger
  - record off-axis L-band signal for post-analysis
- Pulses at both antennas now required for trigger
  - powerful interference rejection
  - disc. thresholds set according to relative aperture
- Thermal noise coincidence rates  $\sim 0.2$  per minute
  - but  $< 1$  /day close to proper moon delay

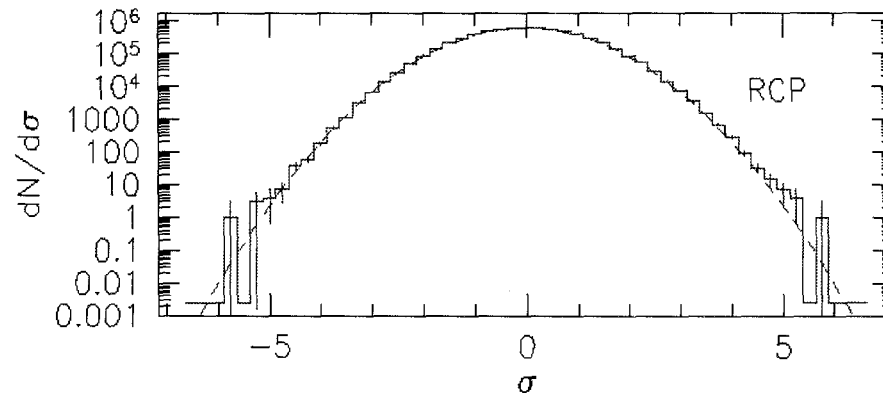
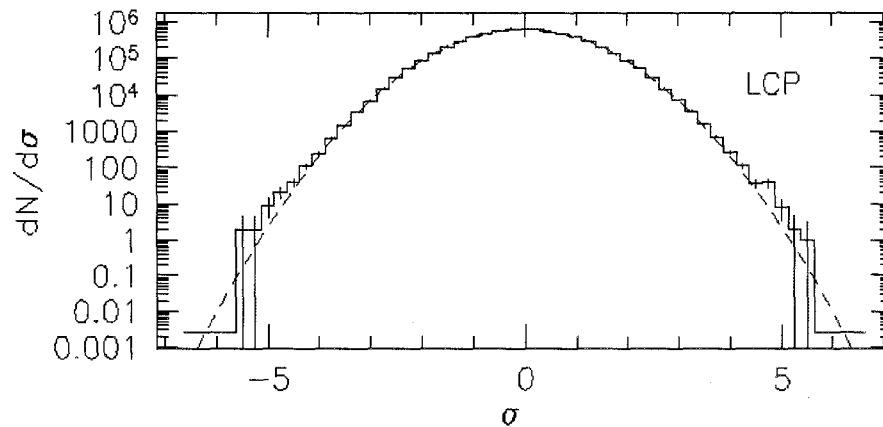
# Realtime dual antenna trigger



- Trigger must accommodate ~136 microsec fiber delay
- 4-fold coincidence formed in two-level trigger with delayed first gate
- 150 microsec window avoids need for realtime delay tracking

# Thermal Noise Statistics

DSS14 Triggered Events Statistics



- Voltages proportional to pulse field strength: pure gaussian:  
 $\Rightarrow dN/dV \sim \exp(-V^2)$

- Square-law detection used for discrimination

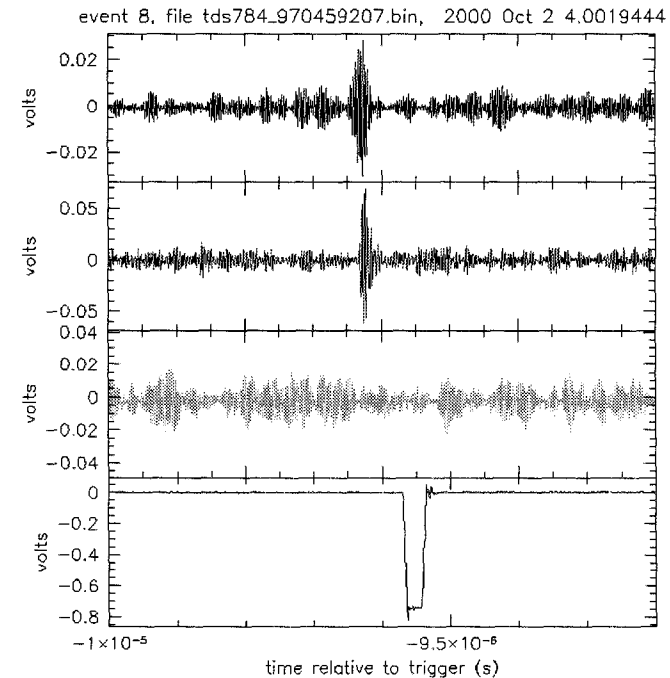
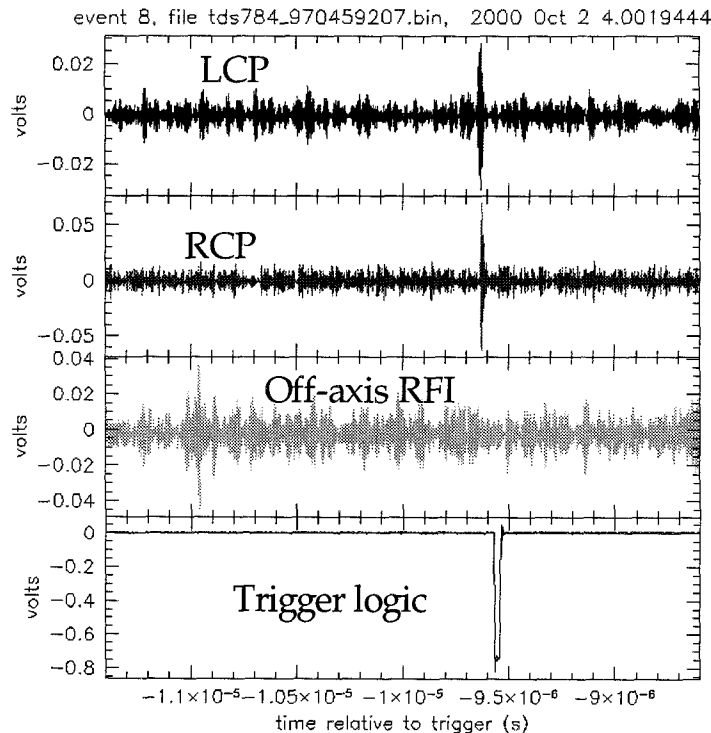
- $\Rightarrow \text{Power} \sim V^2/Z$
- $\Rightarrow dN/dP \sim dN/dV$
- $\sim \exp(-I)$

- Statistics of detected power are exponential

- $\Rightarrow$  5 sigma equivalent significance requires  $\text{SNR} \sim 15$

# Timing & pulse shape calibration

- S-band Monocycle pulser:
  - provides band-limited, 100% linearly polarized pulses
  - checks amp. linearity, net cable delays, band-limited pulse shape, RFI monitor

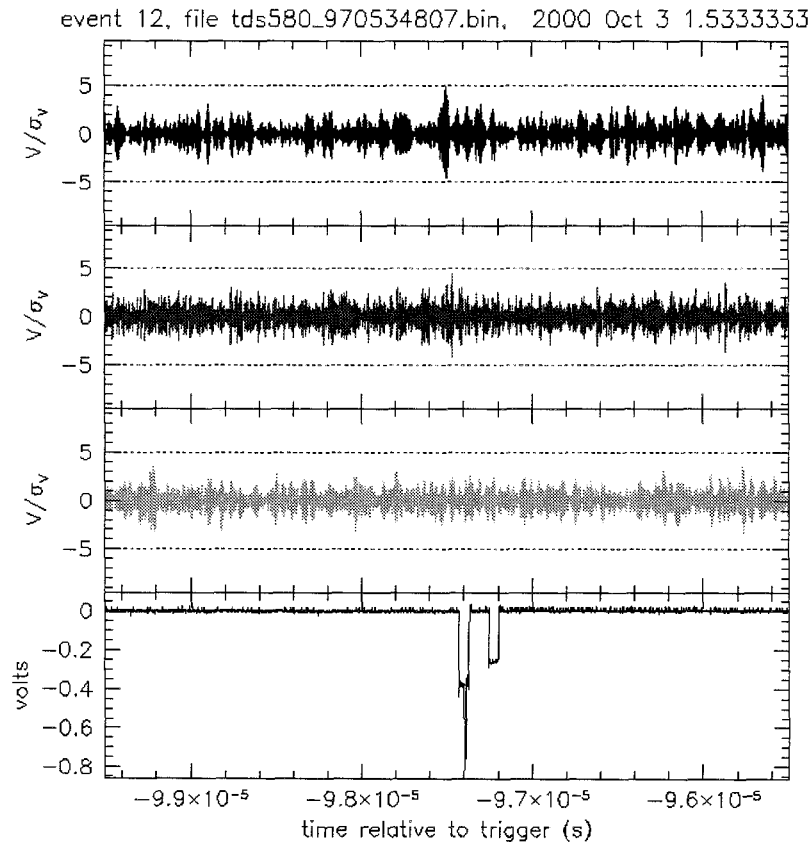


- Zoomed version: LCP pulse is broader (40 MHz BW), RCP narrower (~100MHz BW); also slight timing offset

# Background “trigger:” thermal noise + weak RFI

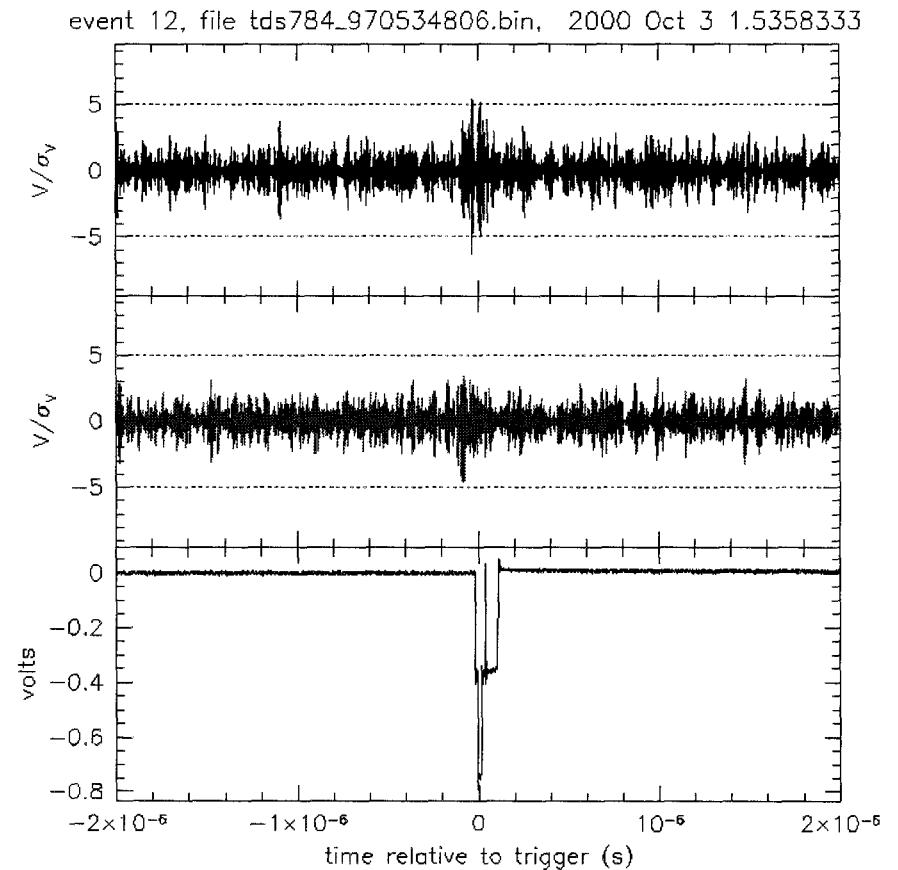
- Most triggers are random thermal or obvious RFI; some less obvious:

DSS14: 70m antenna



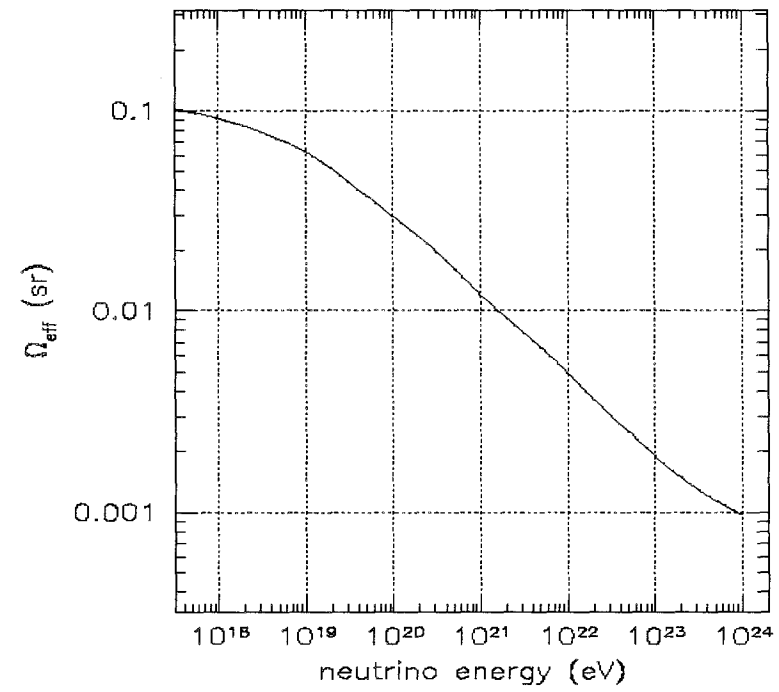
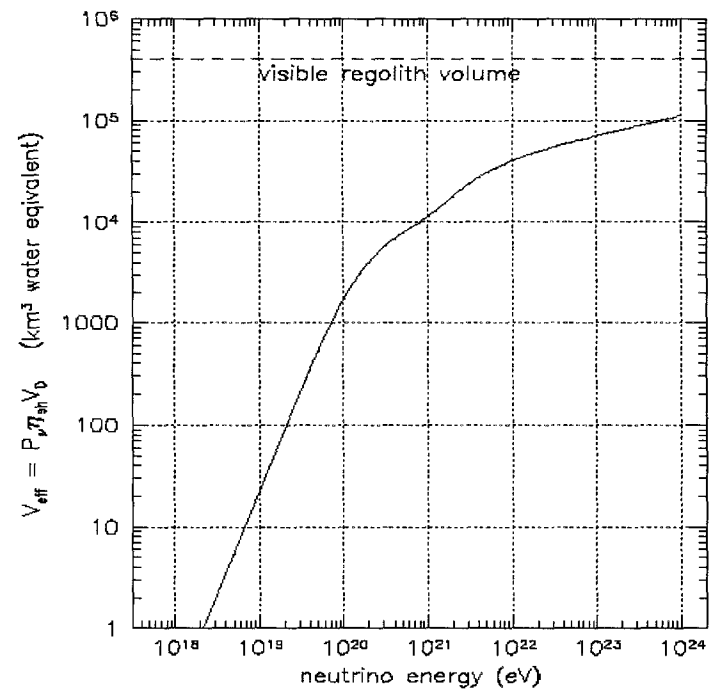
~4-4.5 sigma in both LCP,RCP, no RFI

DSS13: 34m antenna

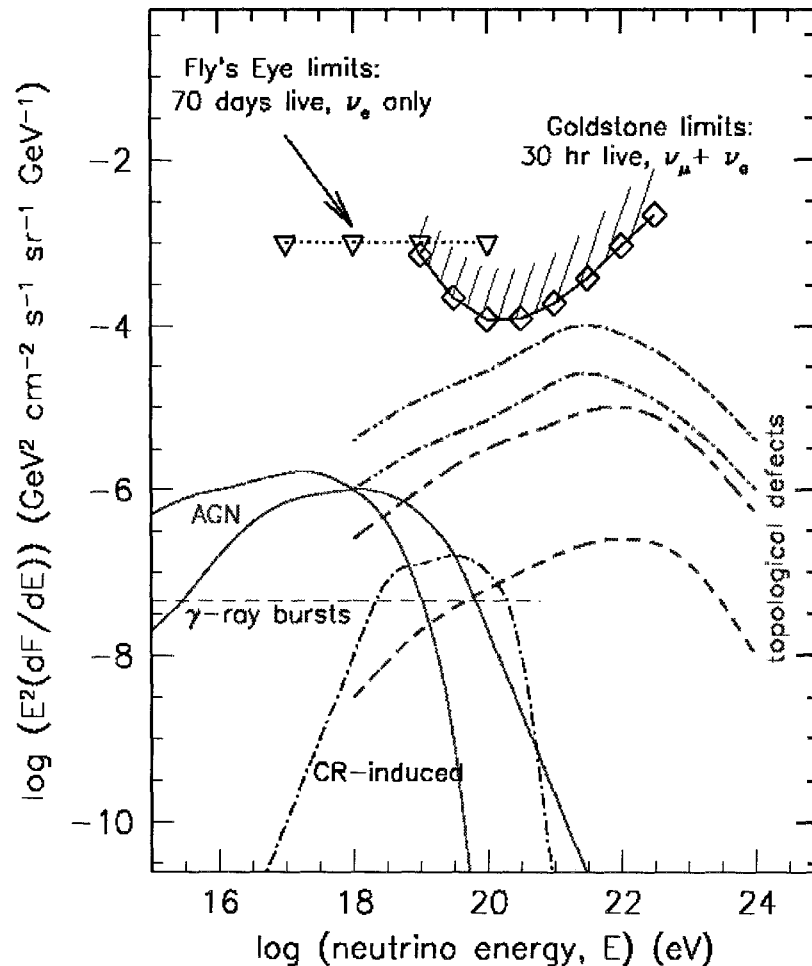


~5 sigma, but *not* band-limited,  
==>prob. RFI, (but no DSS13 RFI monitor)

Effective Lunar Target Volume, Goldstone 70m S-band



# Goldstone diffuse EHE neutrino flux limits



~30 hrs livetime (includes previous data)

- No events above net 5 sigma

**New Monte Carlo estimates:**

- cross-sections 'down' by 30-40%
  - moving target effect!
- Full refraction raytrace, including surface roughness, regolith absorption
- Y-distribution, LPM included

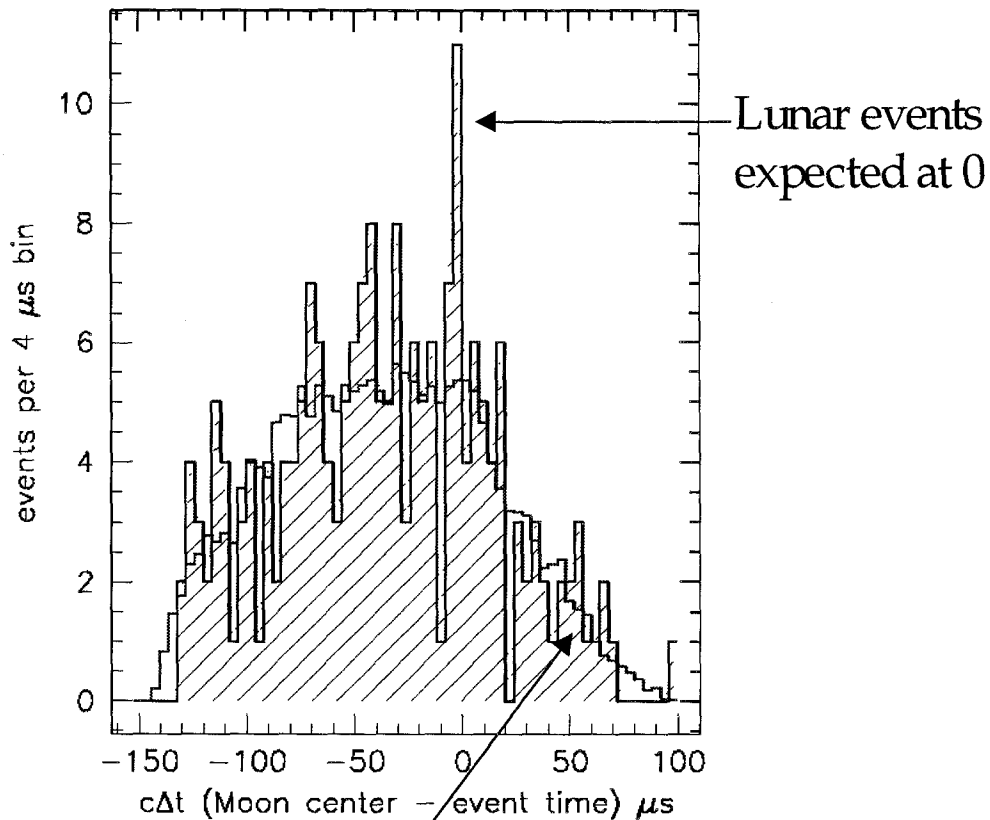
**Limb observations:**

- lower threshold, but much less effective volume (factor of ~1/10)
- 'Weaker' limit but with more confidence

**Fly's Eye limit: needs update!**

- Corrected here (PG) by using published CR aperture, new neutrino xsections

# Small Event analysis of GLUE data



Cuts applied:

- tighter timing
- pulse width close to band-limited
- not obvious RFI

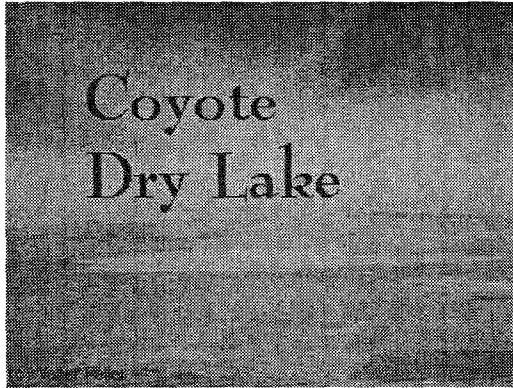
BKG weight determined by randomizing event UT within run period

Some concentration of events near correct delay:

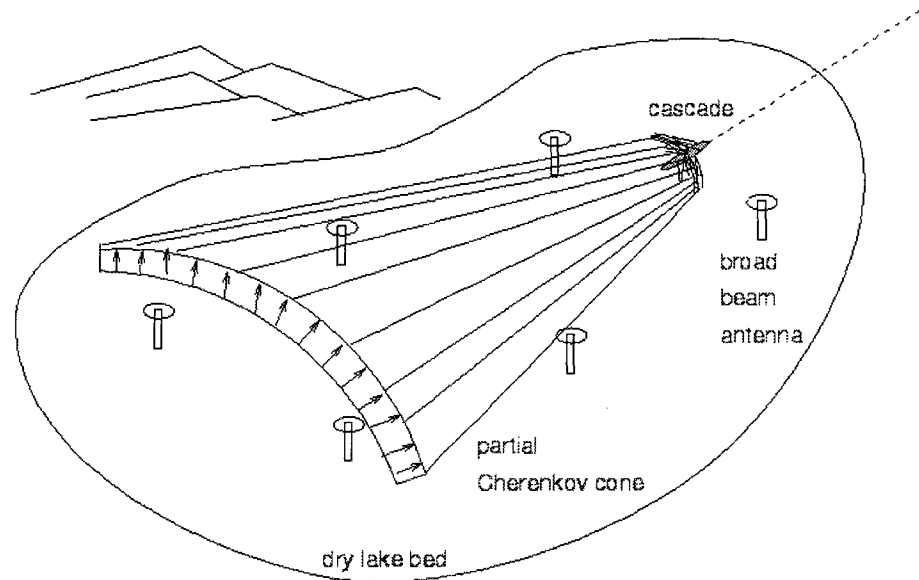
- not significant yet
- ~2 microsec offset hard to explain

• *Are we seeing EHE cosmic rays?*

# Desert Playas (Dry lakes): RF surface Array



Area:  $\sim 160 \text{ km}^2$ , near Barstow



CASCADE IN  $\sim 10 \text{ m}$  SURFACE LAYER + RF REFRACTION

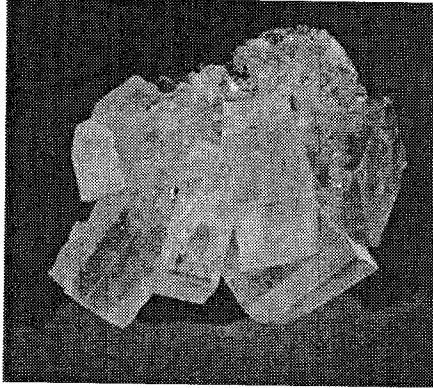


Tracking possible by use of polarization measurements:

Plane of polarization preserves projected track direction

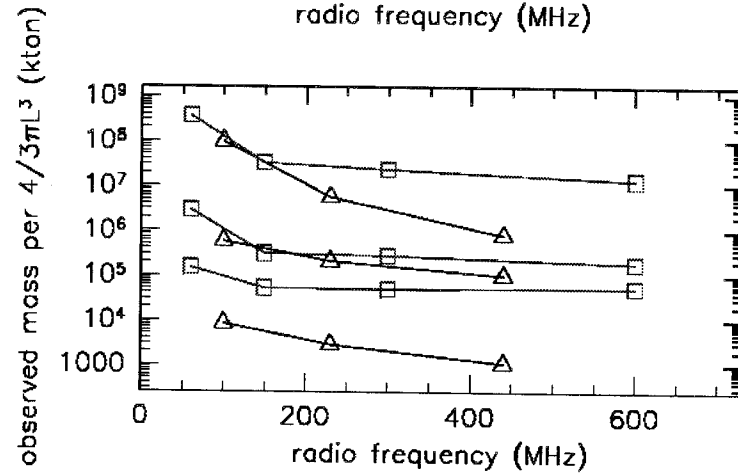
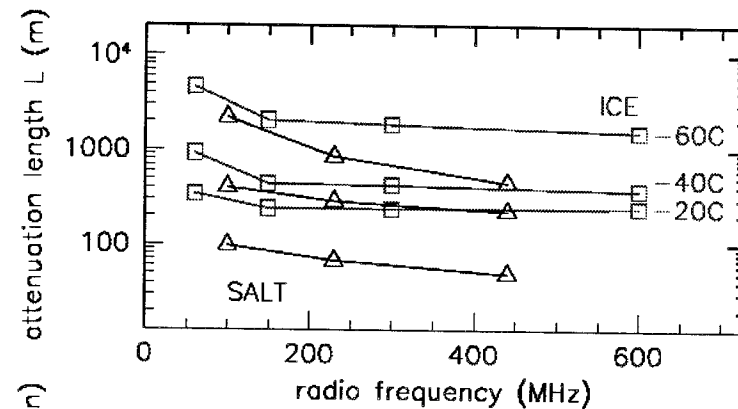
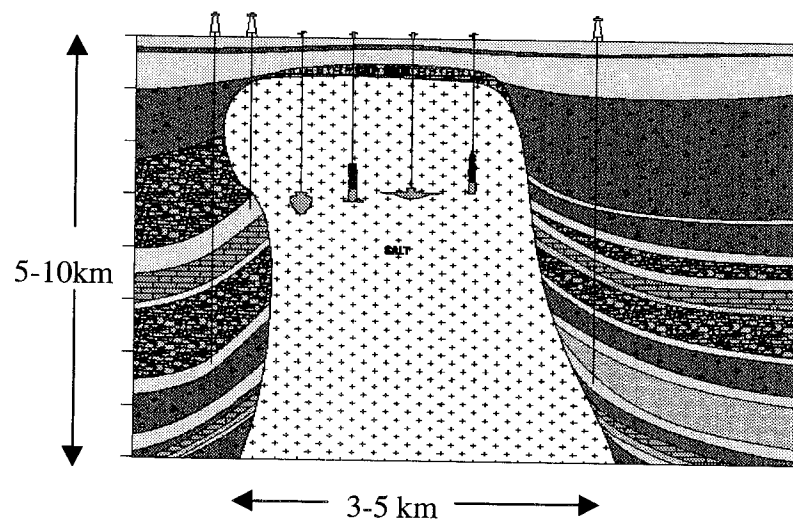
$\sim 3 \text{ cubic kmwe}$ ,  $E_{thr} \sim 1 \text{ PeV}$   
possible for modest array at playa like Coyote Lake!

# Natural Salt Domes: Potential PeV Neutrino Detectors



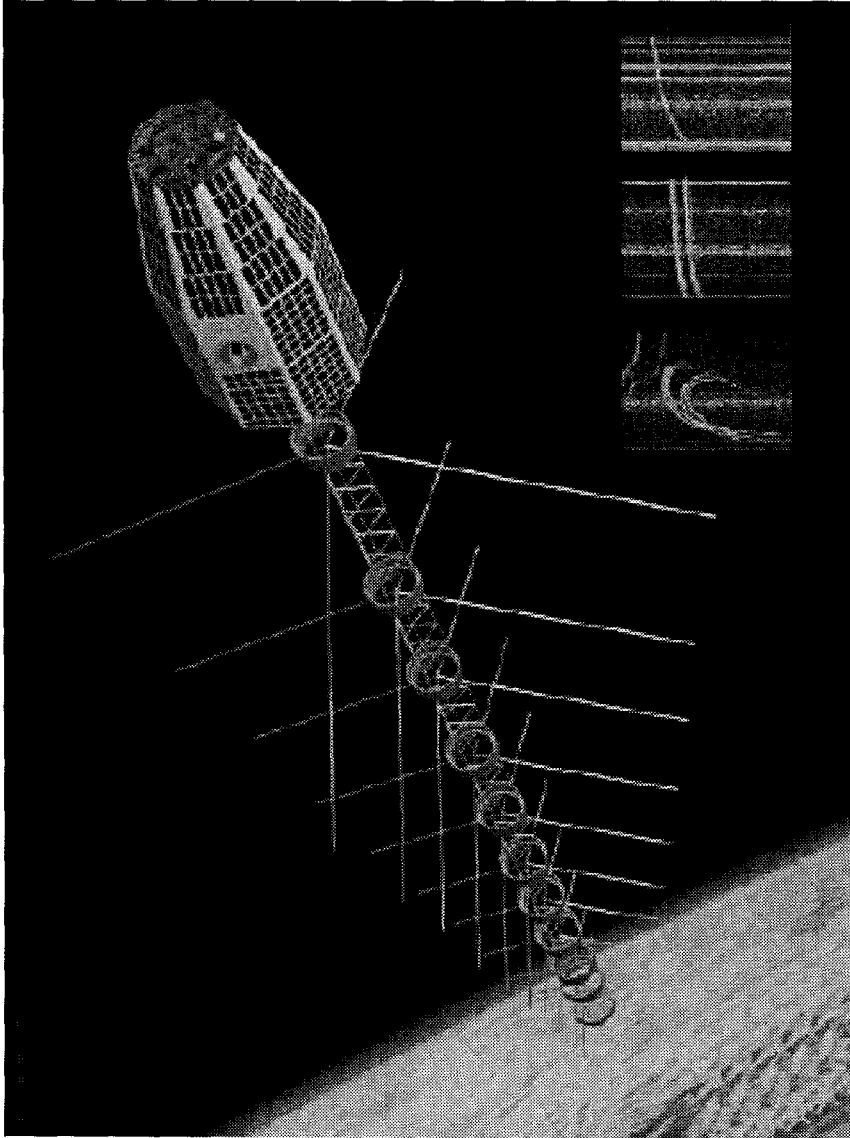
- Natural salt can be extremely low RF loss: ~ as clear as very cold ice, nearly 2 1/2 times as dense

- Typical salt dome halite is comparable to ice at -40C for RF clarity



SALT curves are for (top): purest natural salt; (middle): typical good salt dome; (bottom) best salt bed halite.

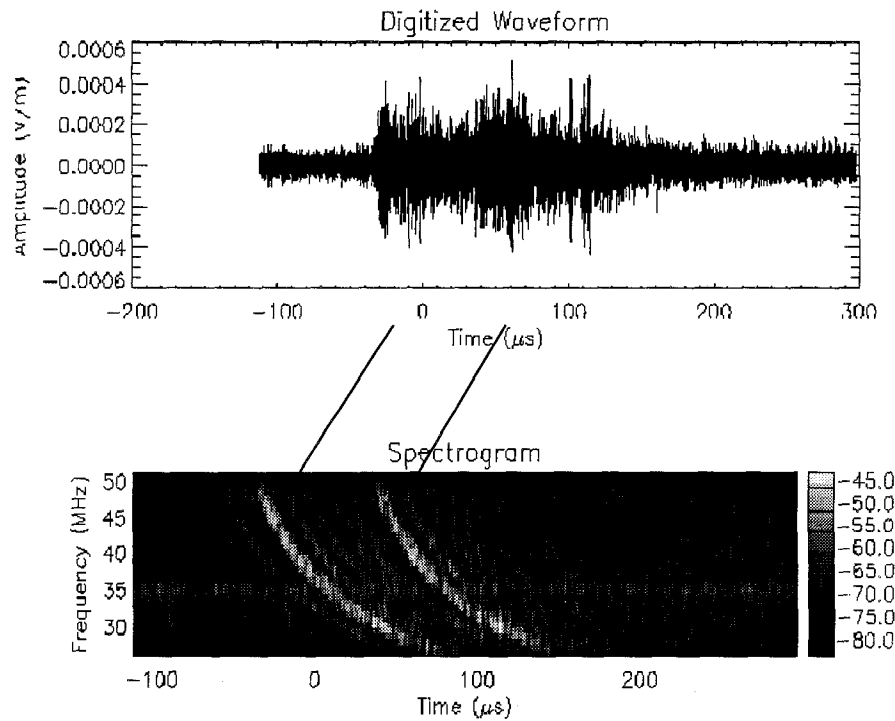
# FORTE: A space-based EHE neutrino & cosmic ray detector?



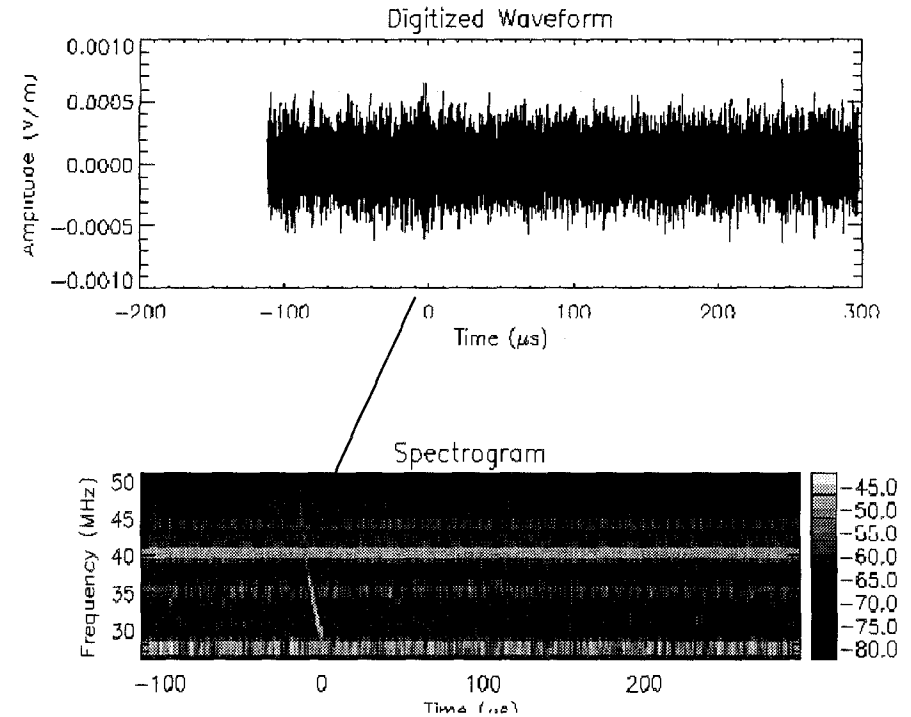
## Fast On-orbit Radio Transient Expt.

- Pegasus launch in 1997
  - 800 km orbit, 3 year planned life
  - Testbed for non-proliferation & verification sensing
  - Dept. of Energy funded, LANL & Sandia construction & operation
  - Scientific program in lightning & related atmospheric discharges
- 30-300MHz range, dual 20 MHz bands, 16 1MHz trigger channels
  - ~2M triggers recorded to date
- FORTE can trigger on radio emission from Giant air showers  $E \sim 100$  EeV
- Preliminary estimates: could be ~50-100 100 EeV cosmic ray events in sample
  - Distinct from lightning, could be recognized as isolated events in clear weather regions far from urban noise
  - Analysis (JPL, LANL) planned this year

# FORTE Data examples

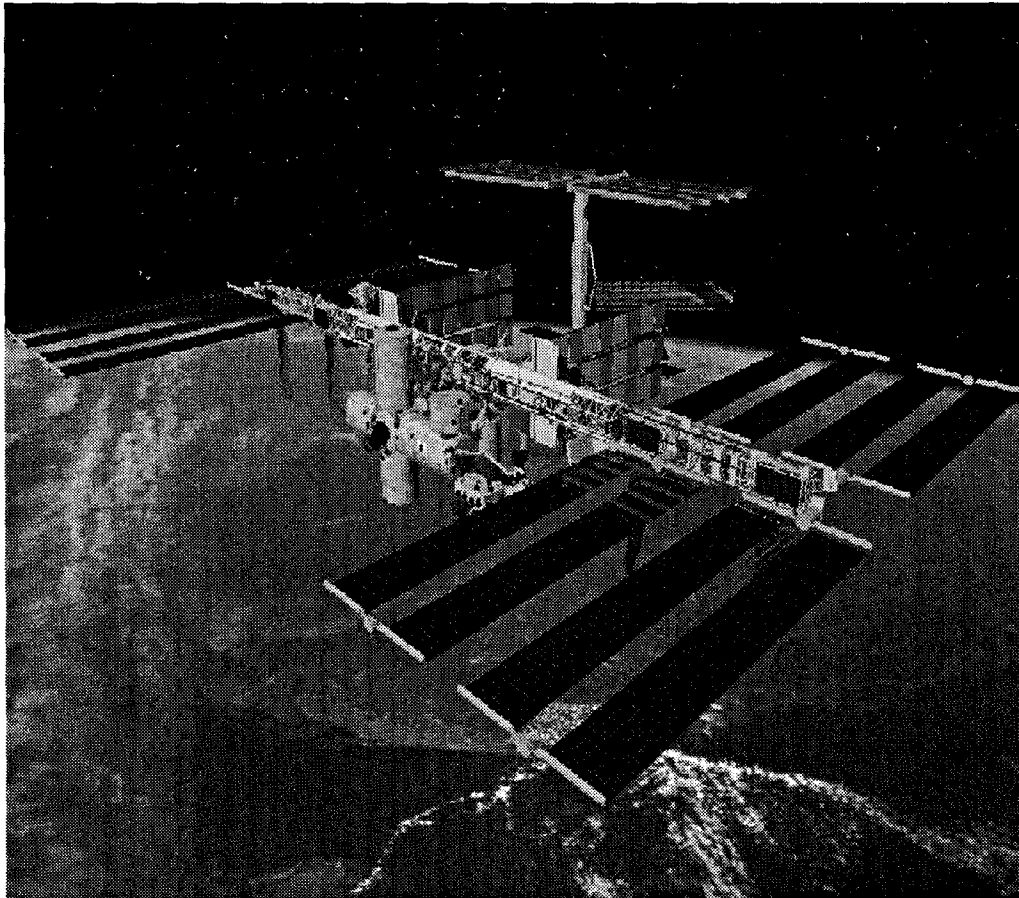


- Typical lightning trigger
  - dispersion (curvature) due to ionosphere
  - multiple strikes
- Correlated to ground-based networks



- Isolated trigger
  - Band-limited, very short duration
  - No pre- or -post-trigger pulses close
  - No related pulses within several sec

## RITA: Radio Impulsive Transient Array, a possible mission of opportunity for the Space Station



- Geosynchrotron & radio Cherenkov from extensive air showers, down & upgoing
- Backward TR from EAS that impact the ocean
- Threshold  $\sim 1e20$  eV
- Area  $\sim 4M$  km<sup>2</sup>, V  $\sim 40,000$  km<sup>3</sup>, water equiv.
- Requires 3 or more elements
  - $\sim 80$  m separation possible
  - $< 5$  deg resolution @ 50 MHz
  - Dual circular polarization
  - Use FORTE approach to deal with anthropic BKG: moving sub-bands for (RFI-quiet) trigger

## Conclusions

- EHE astronomy is a much more compelling challenge than it was just ~10 years ago
  - New models, predictions, techniques
  - GZK mystery has only deepened with time
- Particle physics methods can really “own” this regime of astronomy--there is a natural match
  - both the physics and the detection techniques are HEP
  - sources of EHE neutrinos, hadrons, photons will extend the reach of high energy physics beyond any ground-based machine
- Exploring the physics & tech needed to solve these problems will lead to surprises
  - Effects like that predicted by Askaryan are probably still unknown ==> serendipity will happen!